

Shuttle Wing Leading Edge Root Cause NDE Team Findings and Implementation of Quantitative Flash Infrared Thermography

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Date

3-31-09

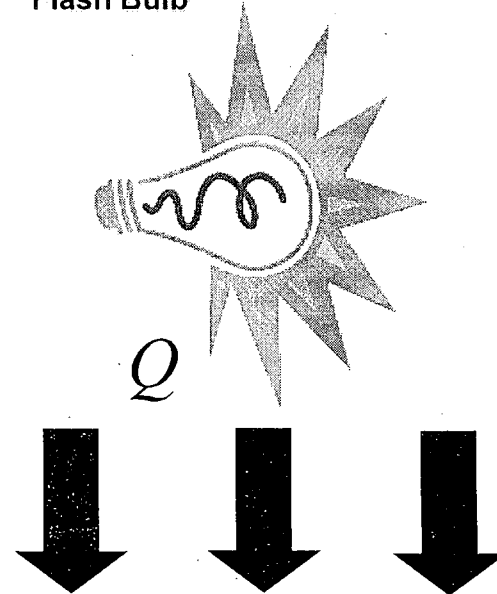
IR Basics

- Three main modes of heat transfer.
 - Conduction
 - Radiation
 - Convection
- Flash thermography is mainly concerned with only the conduction of the heat through the part being inspected.
- For a semi-infinite, defect free sample, the time-dependent surface temperature response to an instantaneous heat pulse is given by

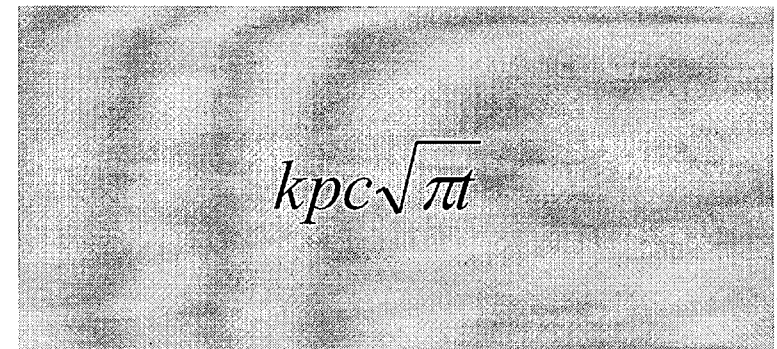
$$T_{Surf}(t) = T_{Surf}(0) + \frac{Q}{kpc\sqrt{\pi t}}$$

- Where Q is the input energy per unit area, k the thermal conductivity, p the density, c the specific heat of the sample and t is time.

Flash Bulb

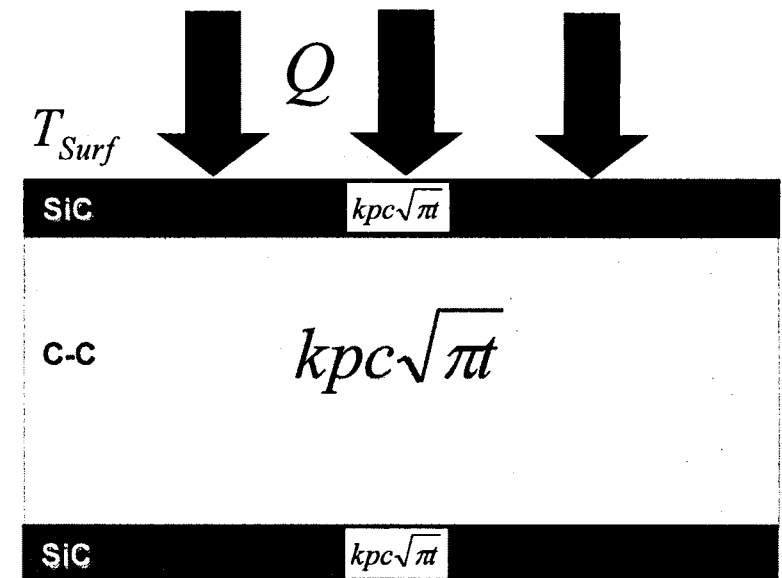
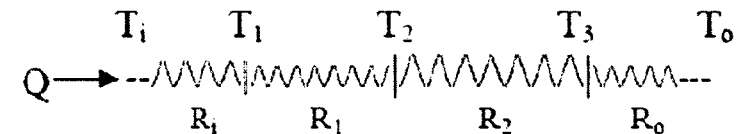
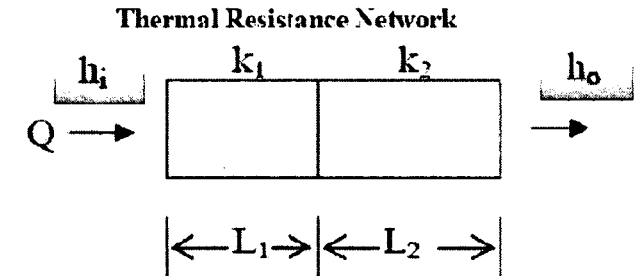


T_{Surf}



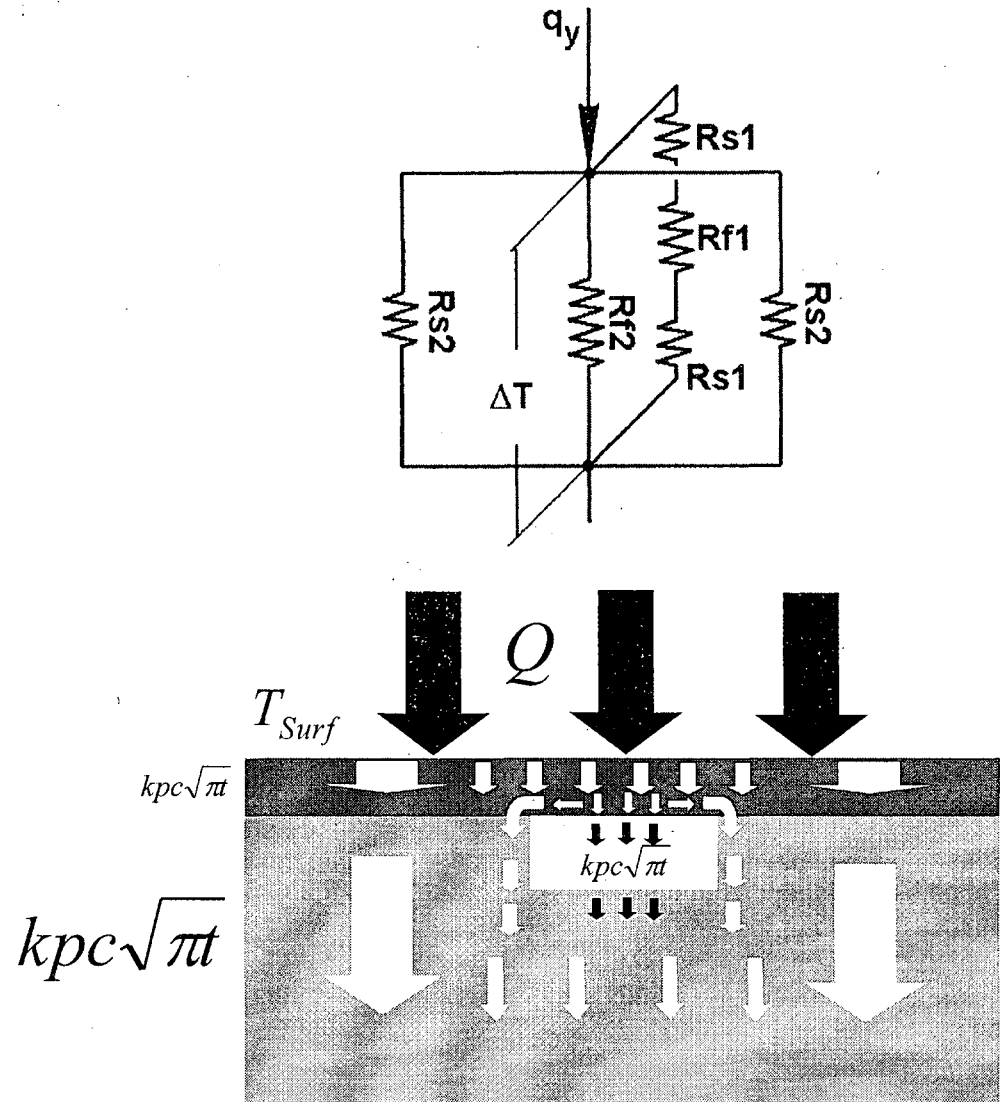
IR Basics Continued

- Given the basic equation complex systems are simply modeled by viewing each section of the material as it's own thermal body.
- These individual systems are dependant on each other and can be modeled in series.
- Due to the layered system of reinforced carbon carbon it is most simply modeled by a two part system.
- Properties for SiC:
 - (k) Surface Normal Thermal Conductivity for SiC = 15.6 W/(m K) (Note:~4.5x Higher than C-C)
 - (k_y) In-plane Thermal Conductivity for SiC = 24.3 W/(m K)
 - (Q) Specific Heat for SiC = 0.69 J/(g K)
 - (p) Density for SiC = 3.2 g/cm³
- Properties for C-C:
 - (k) Surface Normal Thermal Conductivity for C-C = 3.46 W/(m K)
 - (k_y) In-plane Thermal Conductivity for C-C = 5.39 W/(cm K)
 - (Q) Specific Heat for C-C = 0.75 J/(g K)
 - (p) Density = 1.6 g/cm³

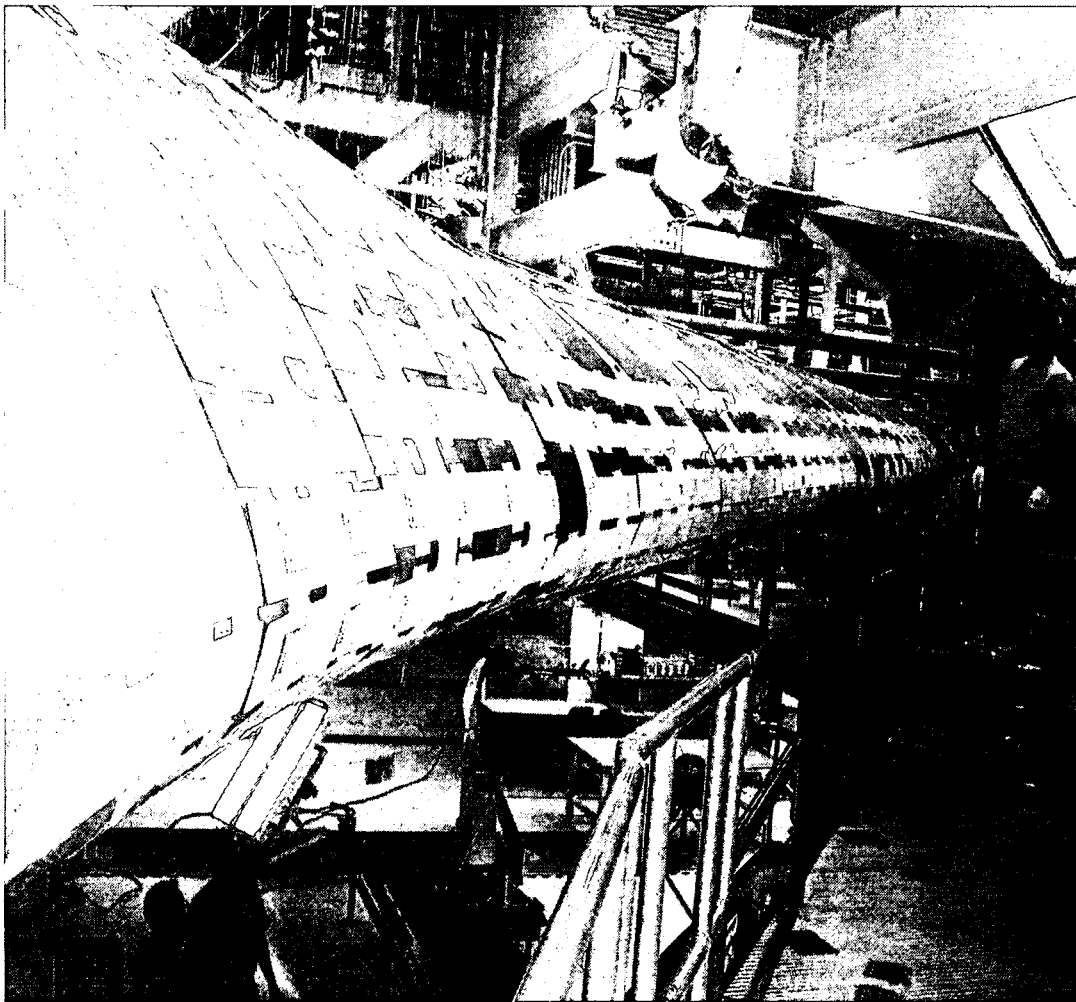


IR Basics Continued – The Defect

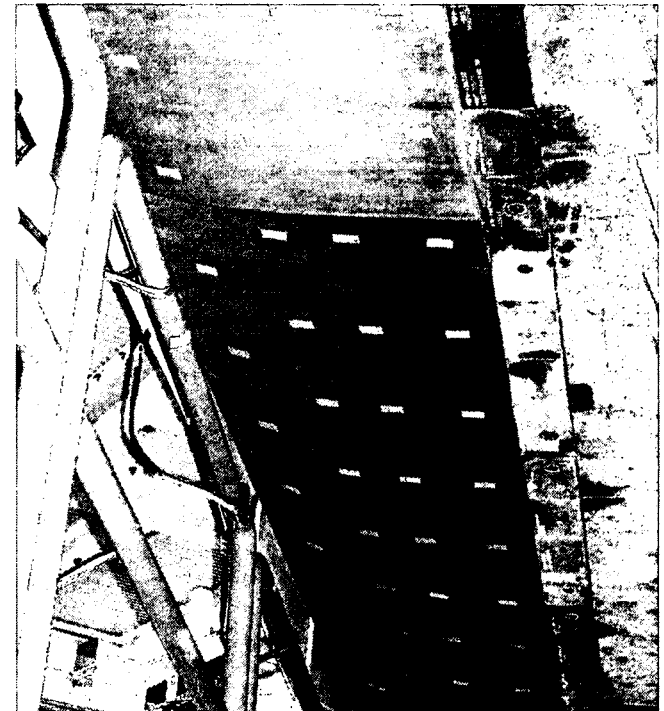
- The addition of a defect changes the dynamics of the problem.
- The addition of a defect can be considered three ways.
 - Void – No Heat Transfer
 - Some Conduction – Air Gap
 - $k = 0.07 - 0.026 \text{ W/ (m K)}$
 - A partial combination of air conduction and material conduction simply referred to as contact resistance.
- Heat energy now has several paths it can follow.
- Some of the heat flows though the gap and some flows around the gap. By flowing around the gap the in-plane (k_y) determines the rate of heat flow.



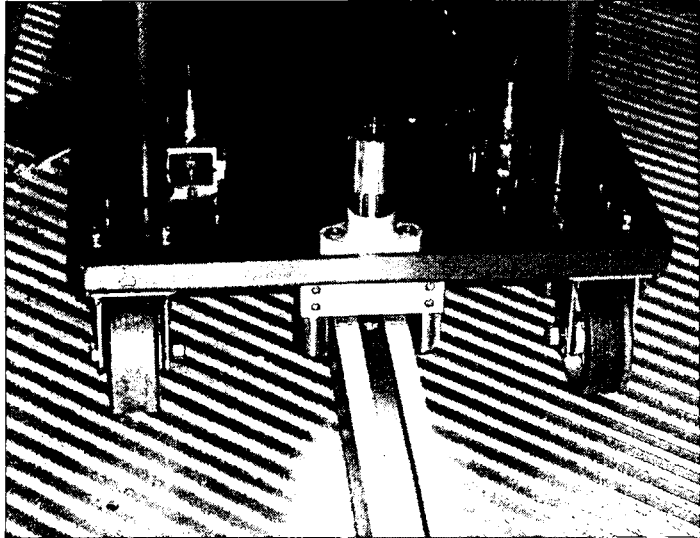
IR Template System



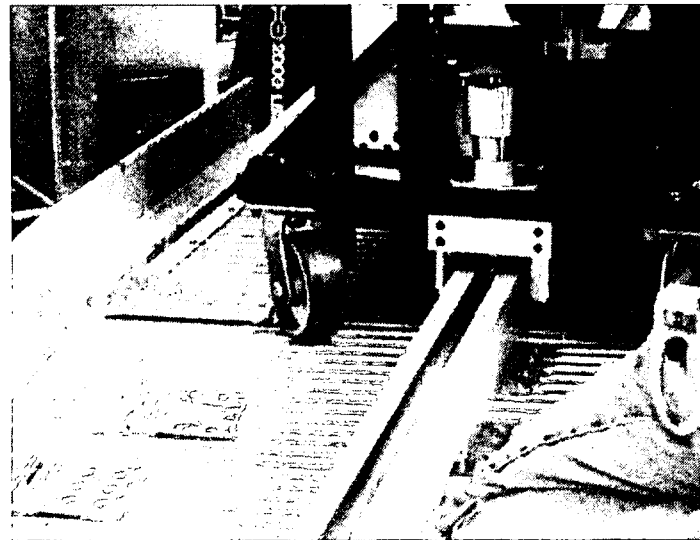
TEMPLATES AFTER PLACEMENT



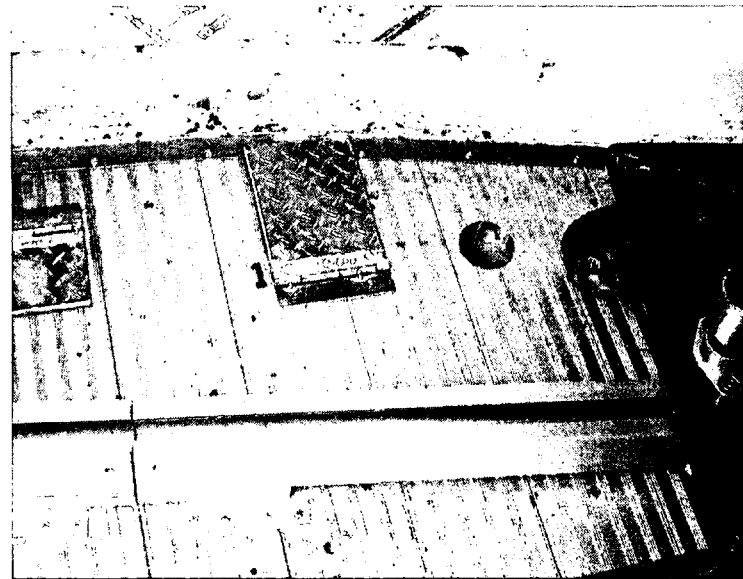
BOTTOM OF WING
REVEALING FLASH
SEQUENCE MARKS
ESTABLISHED ONCE
TEMPLATES ARE
REMOVED



Positioning Cart Slotted
in GSE Railing System



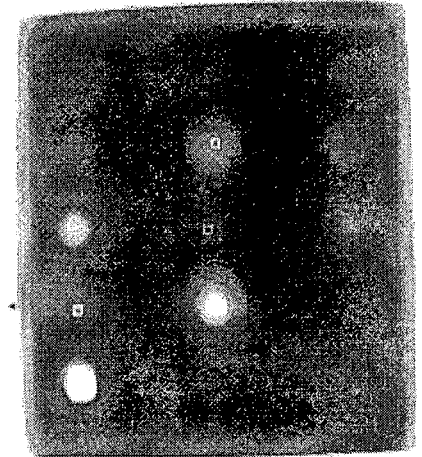
GSE Railing System
Connection



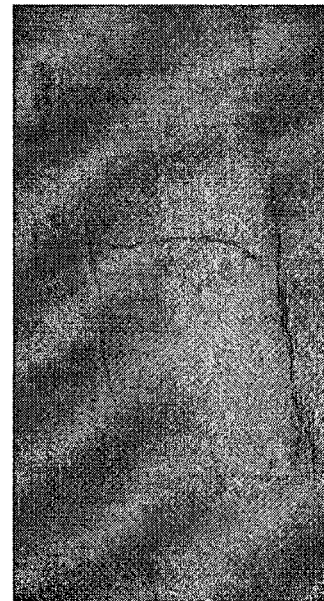
IR – A Qualitative Method

- To this point IR has mainly been a qualitative technique.
- As we have seen that the presence of defects causes changes in the way that heat flows through a given part.
- Comparing the image contrast levels the Level 3 operator can easily see defects in reinforced carbon panels.
- One of the short coming of this method is that the current standards contain defects that are significantly deeper than the current mode of failure.
- Majority of the acreage inspection
- Common Tools
 - T-T Curves
 - Raw Image
 - 1st Derivative
 - 2nd Derivative

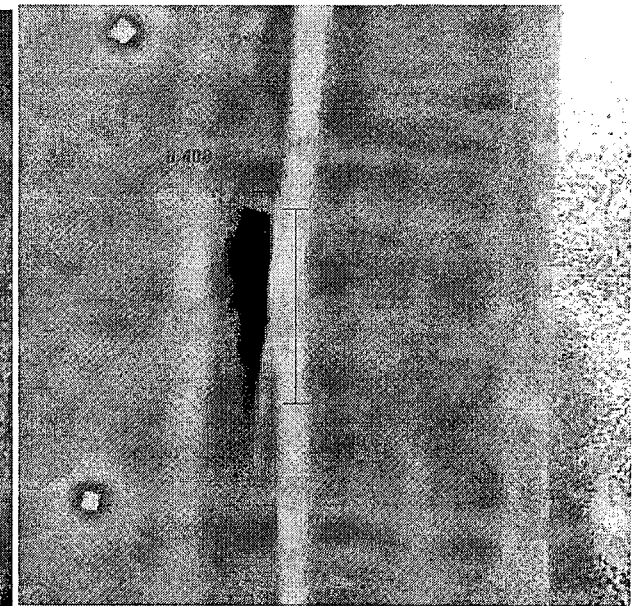
Calibration Image



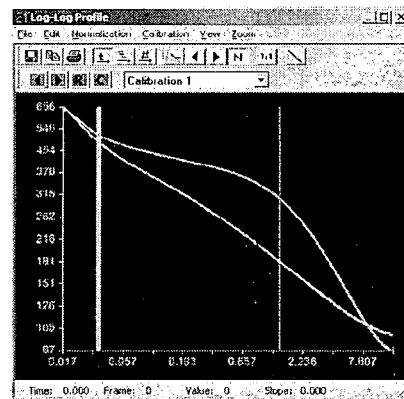
Photo



Second Derivative

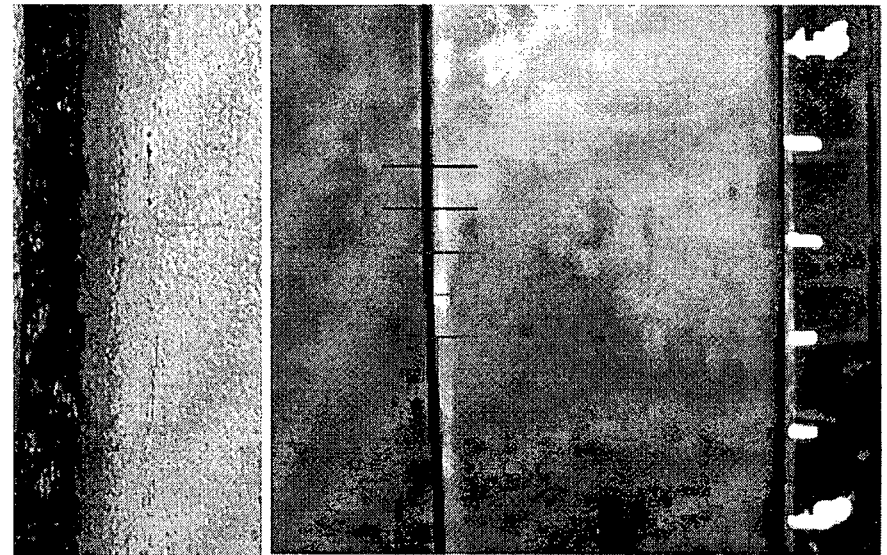
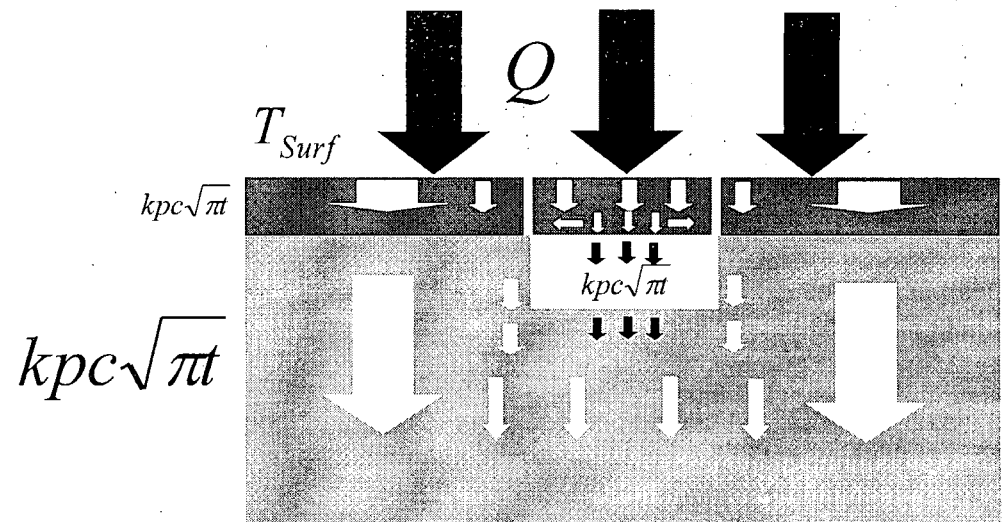


Time Temperature Curve



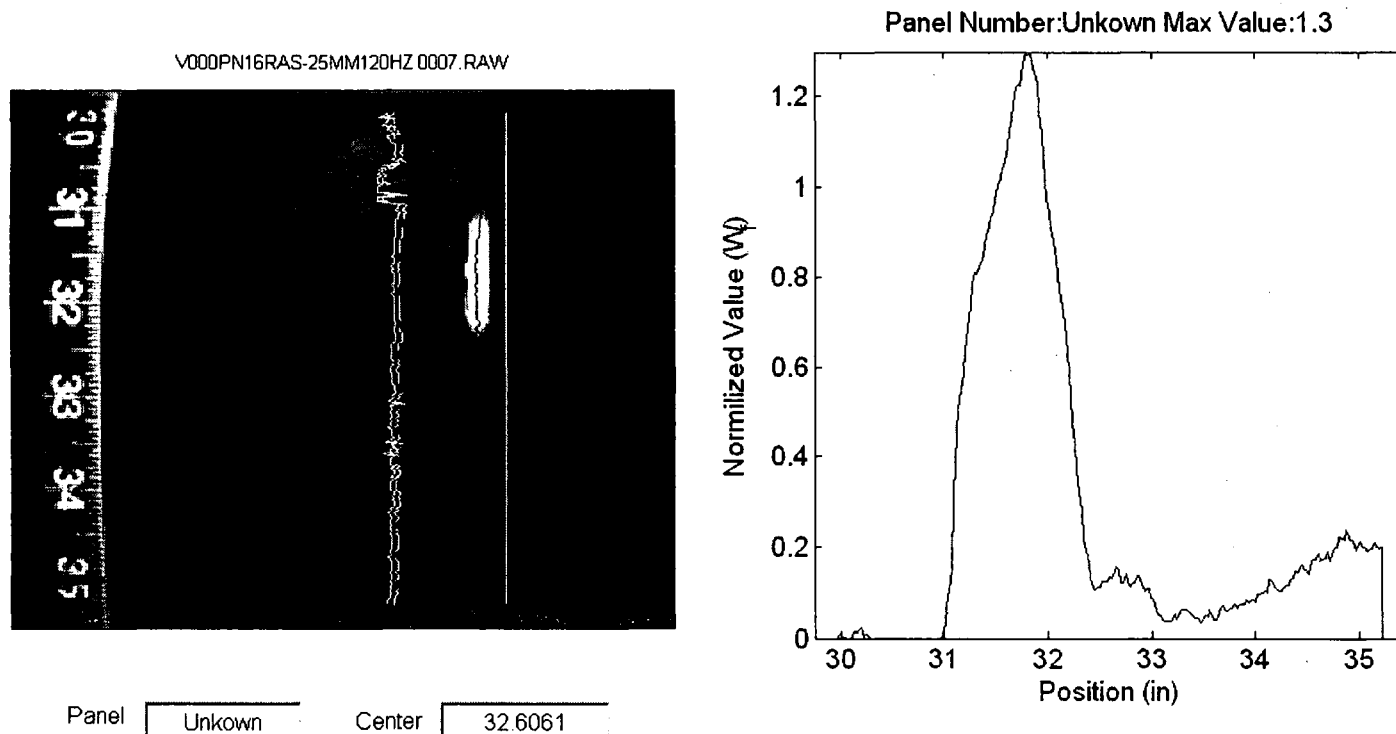
IR Basics Continued – The Defect

- Cracks in the surface of the material will cause the heat in that area to be forced through the underlying defect. This will cause a higher than normal heat build up in that area.
- Loss of lateral heat flow is commonly observed around cracks and craze cracks.
- In a thermographic image cracks and craze cracks generally form very defined lines.
- Occasionally there will be a surface defect that causes a hot spot in the image. These hot spots occur very early in time and do have a very long (persistent) existence. Flakes are noted but not considered a defect.



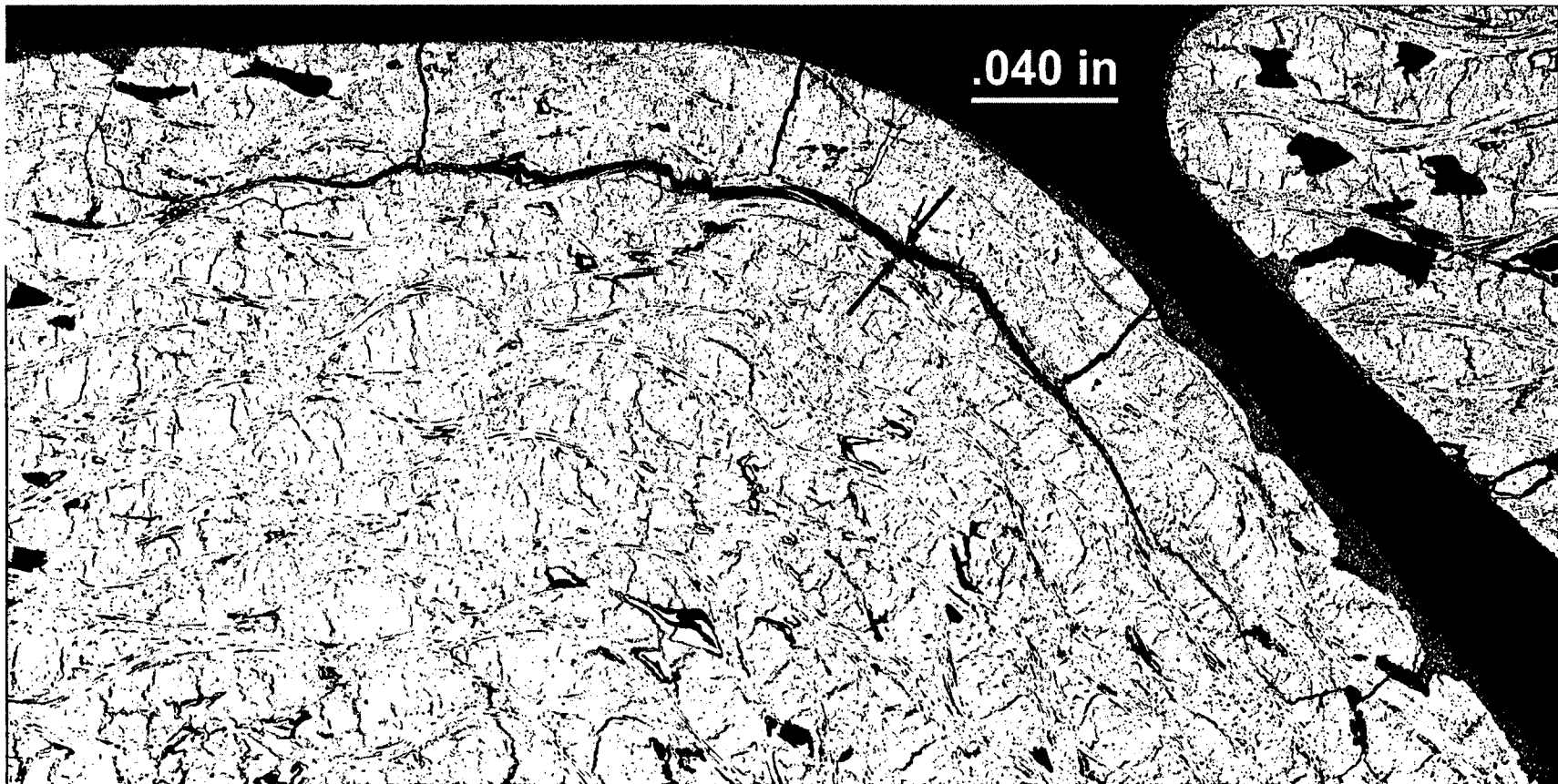
IR – A Quantitative Method

- Using a quantitative method allows for the formation of a metric that has information on the intensity of the defect that cannot be gained by qualitative comparison.
- The establishment of the Normalized Value is a method for establishing a quantitative number for a given indication.



Normalized Value Method – The Analysis Image

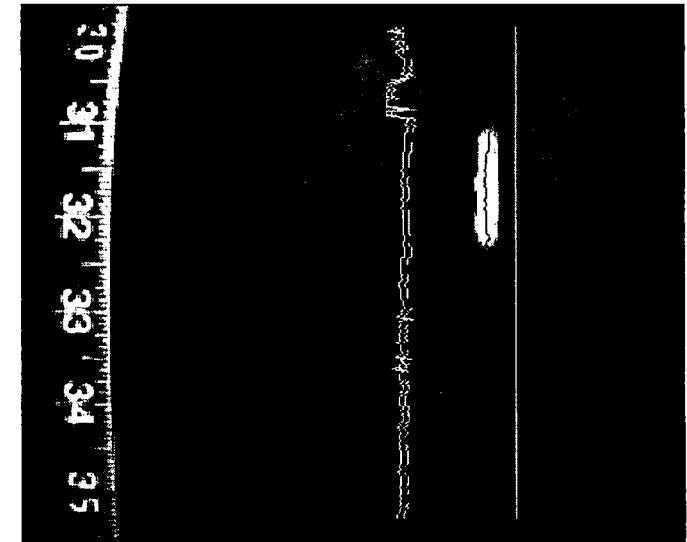
- Given that the main mode of failure is occurring at the SiC – CC interface a specific region in time in which several frames are averaged. This image window opens 0.5s after the IR flash occurs and lasts 0.08s. These frames provide a good view in time to find this defect type.



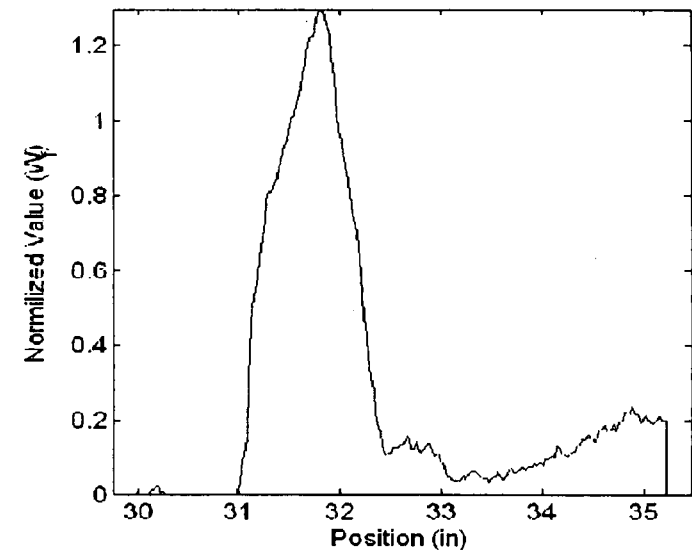
Normalized Value Method – Where the Values Come From

- Many variables can affect the way that a thermographic image is taken. In order to mitigate these affects a reference value is required.
- Due to the geometric curvature heating affect or the presence of a t-seal step and gap the slip side of all panels have a colder region next to the joggle. This cooler region is established as the minimum line (Green)
- From the minimum line the algorithm searches in the horizontal direction to find the maximum value (red).
- Once a maximum has been found a reference value is calculated by stepping in the horizontal direction and averaging a band of values.

$$W_f = \frac{P_{\max}}{P_{\text{ref}}} - 1$$



Panel Number:Unknown Max Value:1.3



Normalized Value Method - Variability

- Several environmental conditions can affect the establishment of the normalized values. The main variables that have been identified are:
 - How Sharply the camera is focused.
 - The angle of the hood relative to the panel being inspected.
 - Location of the defect in the field of view.
 - Material Variability (SiC Thickness, Delamination Depth)
- By shifting to quantitative technique vs. a qualitative technique the IR inspection team has had to tighten it's inspection method to provide more repeatable Wf values.
- Changes thus far include:
 - Specifying the orientation of the hood per shot.
 - Implementation of a Image Quality Indicator.

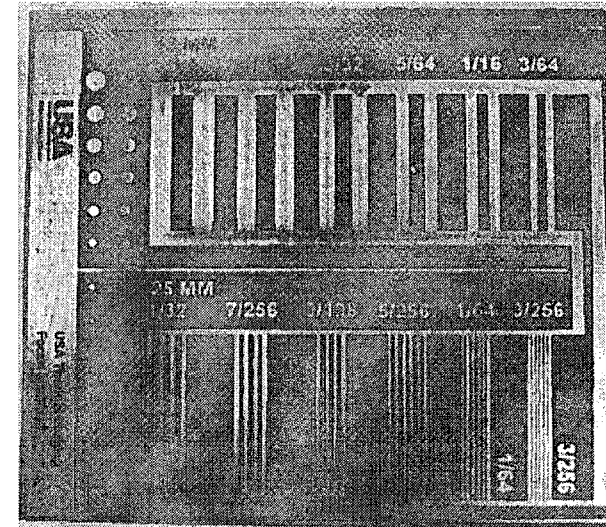
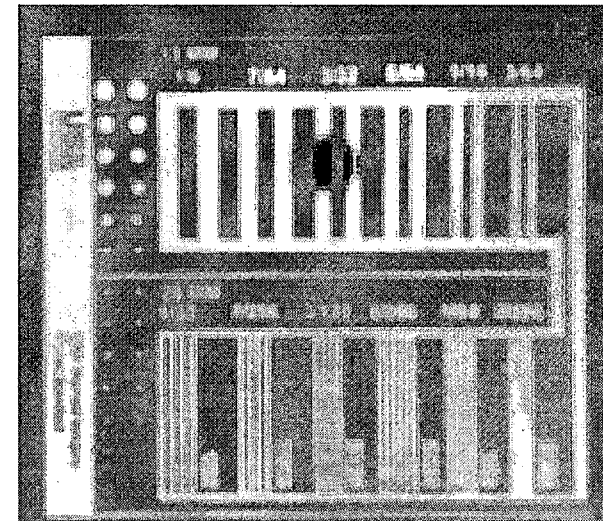


Image Quality Indicator



LaRC JETI (Joggle Edge Technique Inspection)

- The LaRC JETI software is a matlab routine that performs all of the analysis of these thermographic images.
- This software was original authored at Langley Research by Bill Winfree and has become a joint USA/Langley Effort.
- Each orbiter IR inspection consists of 326 13mm images per wing. 160 of these images contain slip side joggle information.
- For an entire orbiter this would require additional analysis of 320 images total.
- Prior to the establishment of this software this normalized value inspection of the joggle regions required two inspectors for two weeks. Totalling ~160 man hours or more.
- This software runs the required routines and then shows the inspector the panels that need further inspection.
- A Level III inspector reviews selected panels.
- Analysis time has been reduced to ~5 man hours for an over all improvement of 32x.
- This program also includes a master database for accurate tracking of values.

The screenshot shows the LaRC JETI software interface. The title bar reads "LaRC JETI" with menu options: File, Operation Mode, Orbiter Number, Edit Parameters, Camera Properties. The main window is titled "Joggle Edge Thermal Indication".

Data Folders:

- Post-mission STS- []
- Left Wing Folder: Null_25mm.mat
- Right Wing Folder: []
- Output Folder: P:\Root Cause Investigation\Standard Pieces\Arc Jet Samples\Root Cause Panel16R
- 11 LW Files Found 0 RW Files Found

Analyze Data:

- Analyze Data []
- Remove Flakes []
- Display Results []

Status:

- ☒ Building File List
- ☒ Detecting Joggle Edges (LW)
- ☒ Calculating Amplitude Values
- ☒ Writing Structure File
- ☐ Detecting Joggle Edges (RW)
- 122 Frame Rate (hz)

Slip Side Indications Summary:

	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Totals		
																	# Shots	# Panels	
LW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	11
RW																			

v1.0 Feb 22, 2008

Repeatability

- Repeat data was collected on OV-105 STS-126 in order to help Larry Green determine the statistical variability of the on orbiter normalized values. Several inspectors ran the same data sets and the differences between the inspectors was analyzed on the repeat shots. The current numbers indicate that in the worst case the repeatability of the line scan technique with respect to orbiter data is +/- 0.05 Wf.
- Follow on work will occur on this Post flight OV-103 STS-119. We have predetermined select shots to repeat. We will also be repeating locations that are above > 0.15 Wf. On this set we will also be working on the repeatability of 25mm data.

3 Inspector Maximum Uncertainties same Shot & Instance, Max of StDev, (Rmax – Rmin)/2

Group 1 Repeats

- 06L+316: 0.03, 0.02 Wf
- 06R+317: 0.05, 0.05 Wf
- 09R+243: 0.00, 0.00 Wf
- 09R+249: 0.02, 0.01 Wf
- 14L+103: 0.00, 0.00 Wf
- 14L+105: 0.00, 0.00 Wf
- 15L+017: 0.01, 0.01 Wf
- 15L+018: 0.00, 0.00 Wf
- 17R+046: 0.01, 0.01 Wf
- 17R+048: 0.00, 0.00 Wf, max of all =0.05, 0.05

Group 2 Repeats

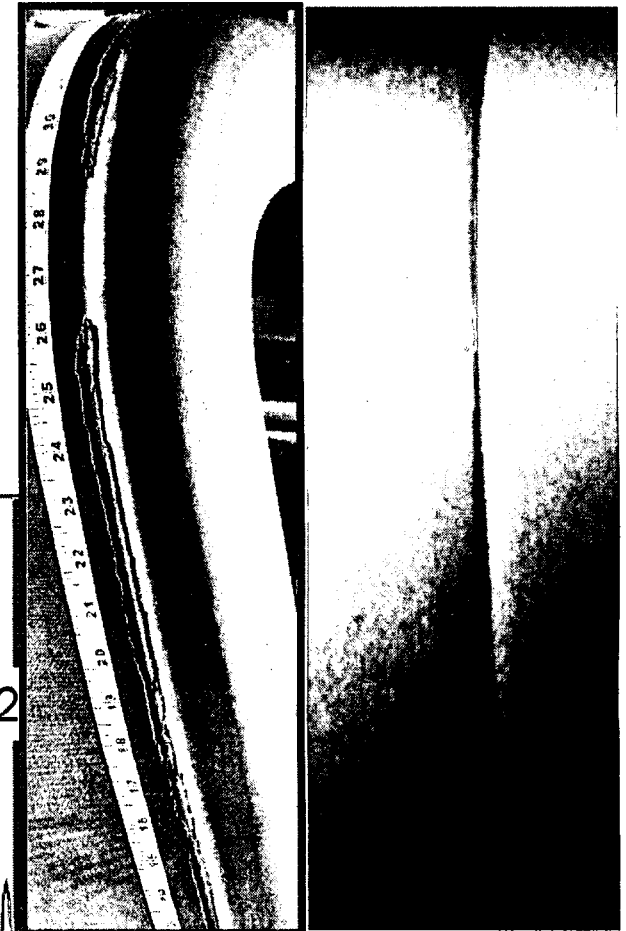
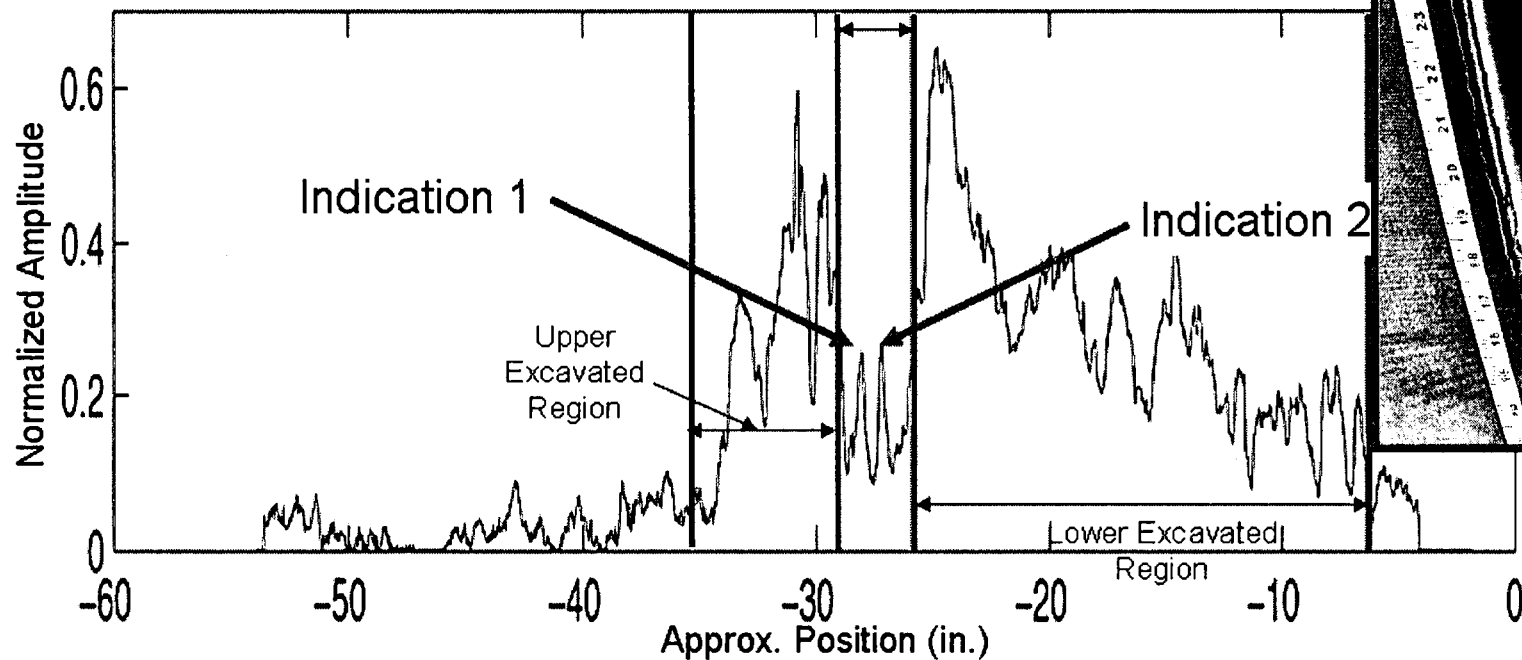
- 06L+274: 0.00, 0.00 Wf
- 06R+312: 0.00, 0.00 Wf
- 11L+192: 0.00, 0.00 Wf
- 11R+215: 0.00, 0.00 Wf
- 12L+204: 0.00, 0.00 Wf
- 13R+195: 0.00, 0.00 Wf
- 13L+196: 0.00, 0.00 Wf
- 15L+022: 0.00, 0.00 Wf
- 16R+123: 0.00, 0.00 Wf
- 17R+047: 0.03, 0.02 Wf, max of all = 0.03, 0.02

Life Expectancy Based on IR Data

- By collecting and comparing previous IR indications may lead to a statistical method for intelligent inventory stocking.
- Analyzing the variances in historical IR data it becomes possible to make predictions on which panels will have the shortest life expectancies.
- The main goal of this work would be to help determine how many and of which type of panels would need to be purchased based on the current inventory of panels and the probability of generating a high indication.
- This will be reflected on a per orbiter and per panel basis.
- We are also including analysis on the general trend of the normalized values on the orbiter.
 - If the findings reflect a general trending this would most likely be attributed to Aging Orbiter / Aging RCC.
 - Separations from this behavior may help to pin point “Bad Actor” panels and special areas of interest that may require more careful inspection.

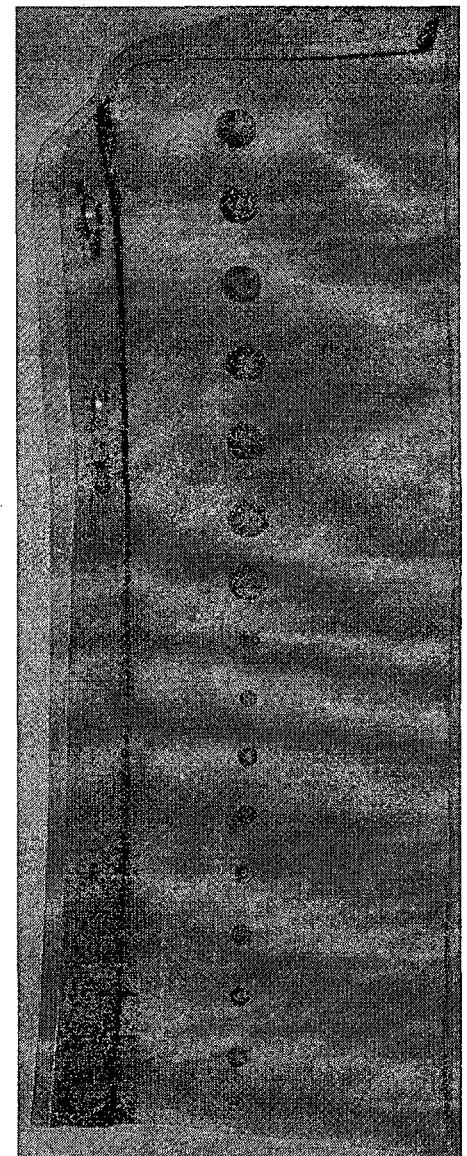
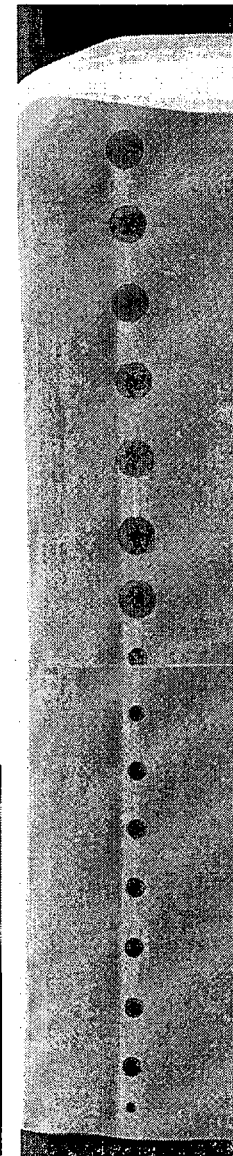
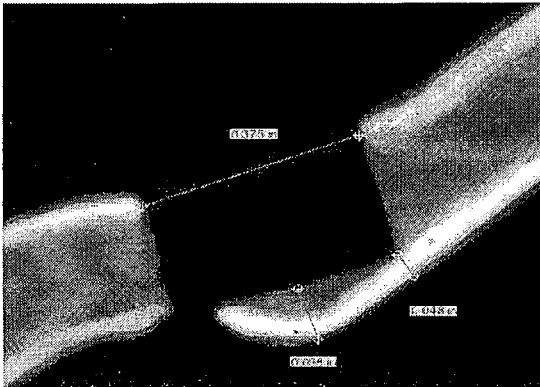
Normalized Value Method – 0.20 Threshold

- Panel 8R Post Flight STS-114 had a very strong thermal indication a majority of this indication was masked by the t-seal and was later removed by dental picking.
- A small section of this area was left in tact and assumed to be delaminated.
- In this region the line scan value was 0.20



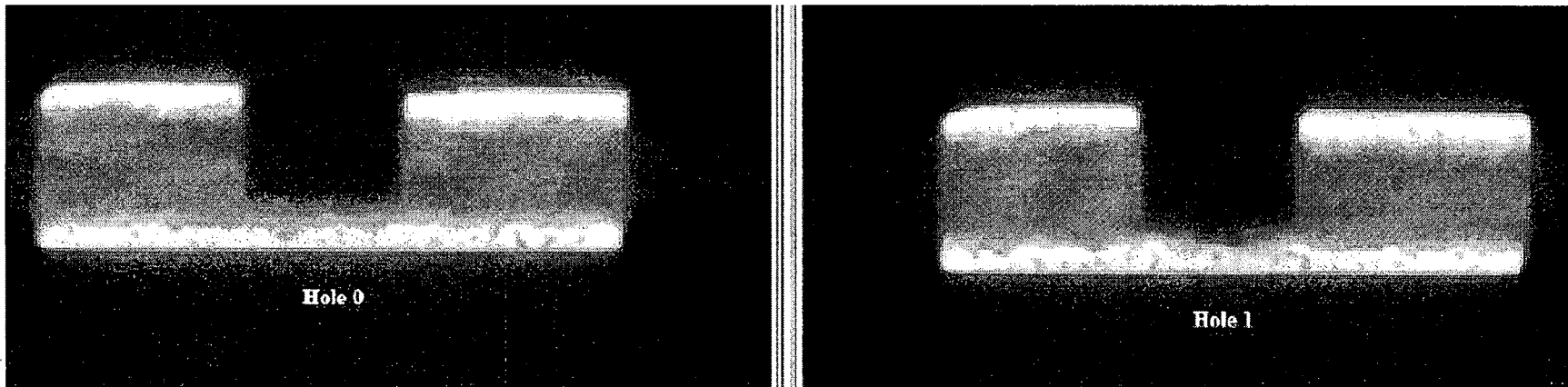
Slip Side Joggle Samples

- Round bottom holes are being used in the joggle region in order to accommodate the curvature of the slip region.
- The thermal signature of a round bottom hole will be different than that of a flat bottom hole. It is not known yet if an appropriate adjustment factor can be established.
- Inspection of these samples will be completed both with and without the presence of the T-Seal.
- In addition a study is currently being conducted to quantify the affect of the T-Seal gap on the magnitude of the Normalized Values.



Slip Side Joggle Standards Manufacture

- Laser ablation is a technique where a tuned laser is applied to the residual carbon material in order to oblate it away. The laser is tuned such that it will remove C-C and not SiC.
- Mound laser photonics took there first cut at cleaning out one of the larger holes on 6L. Due to concerns that they where getting to close to the SiC coating layer we had the part shipped back to KSC to perform an intermediate CT to see how much material remains.
- The laser ablation worked fairly well although there is some small about of residual material remaining. Removing the remaining material did have a significant effect on the normalized response of the standard.
- We are proceeding to procure funding and are going to perform the laser ablation technique all the holes in the standard.



Step and Gap Study

- This study was designed to explore the effect that the WLE T-Seal plays in masking the magnitude of flash thermography indications in the slip side joggle region of the WLE RCC panels.
- Both the 6L and 13L RBH standards have been completed.
- Current Panel List:
 - 17L – Complete, Included in this Report
 - 12L – Panel and Need T-Seal
 - 9R – Need Panel and T-Seal
 - 9L – Need Panel and T-Seal
 - 13R – Need Panel and T-Seal
 - 14L – Need Panel and T-Seal
 - 17R – Need Panel and T-Seal
 - 10R (SN:105P10R006) OV-104 – Need Panel and T-Seal
 - 10R (SN:SPRP10R005) OV-105 – Need Panel and T-Seal

Step and Gap Study - Test Setup

- Gap is established by using USA step and gap shims. The shims come in different color coded thicknesses.
- Using combinations of the shims 5 gap variation are studied: 0.025", 0.075", 0.125", 0.175, 0.225".
- Panel and t-seal are clamped together with shims in place to maintain spacing during testing. Shim sets were specially trimmed to fit in the gap along the joggle region and placed in the gap but out of the FOV of the Thermal Camera. Gaps were also checked during testing between shots by running a shim along the gap.

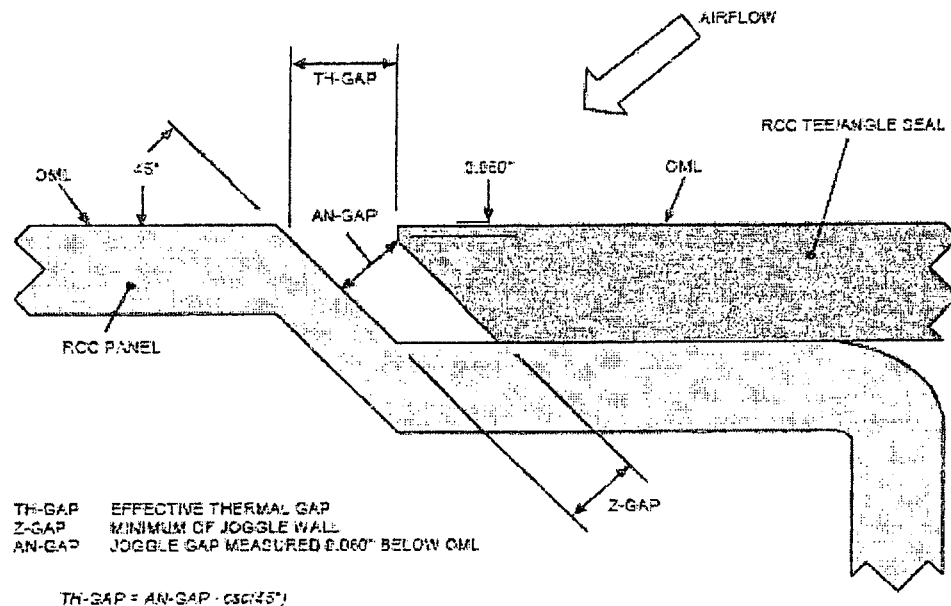
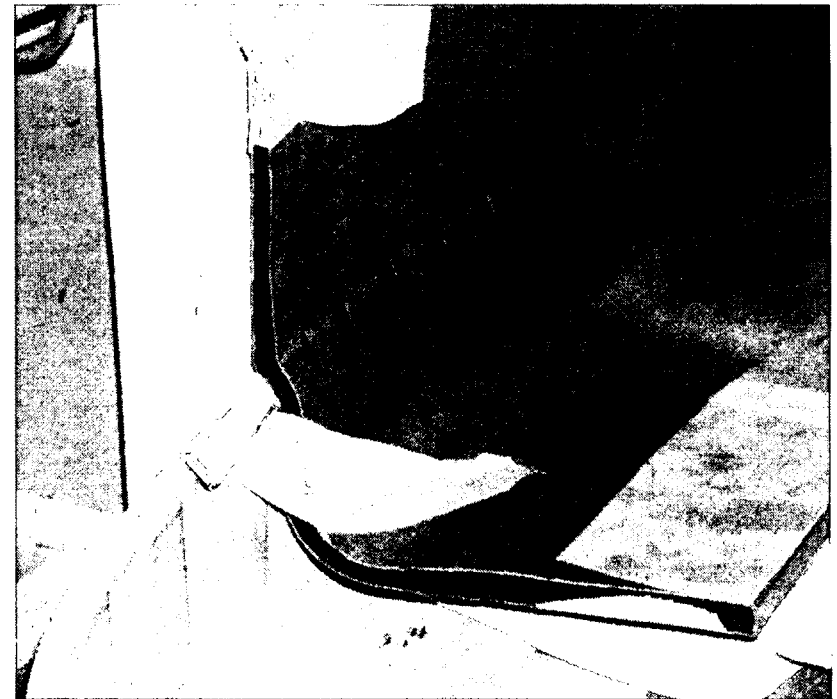
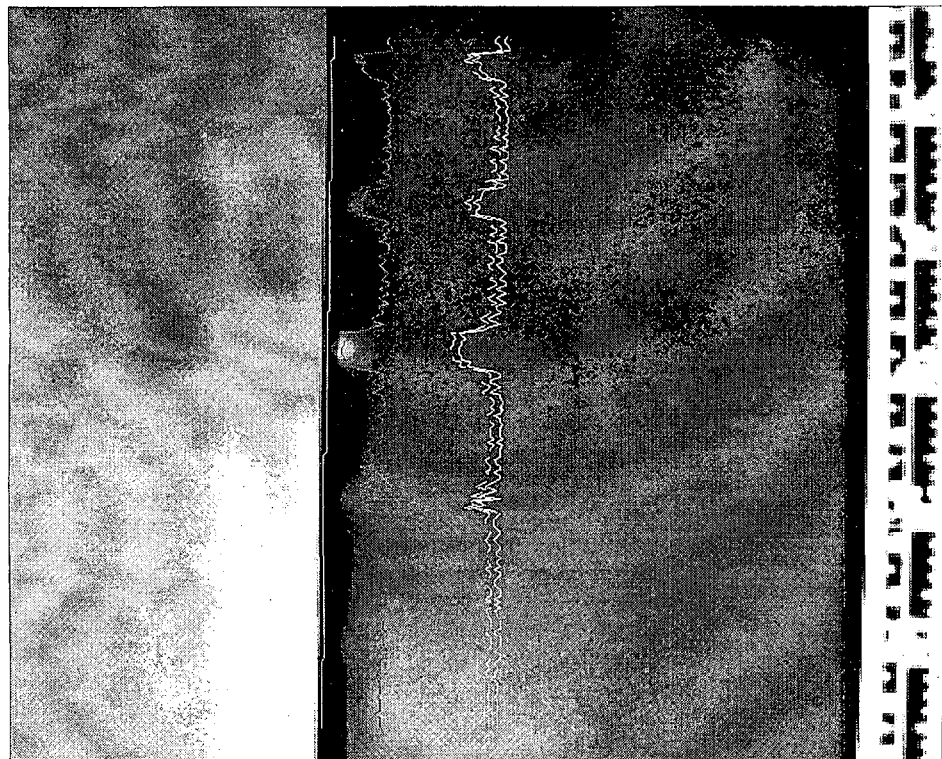


Figure 60-1, AN Inclined Gap, From Figure 13 in ML0301-0023
(For Reference Only)

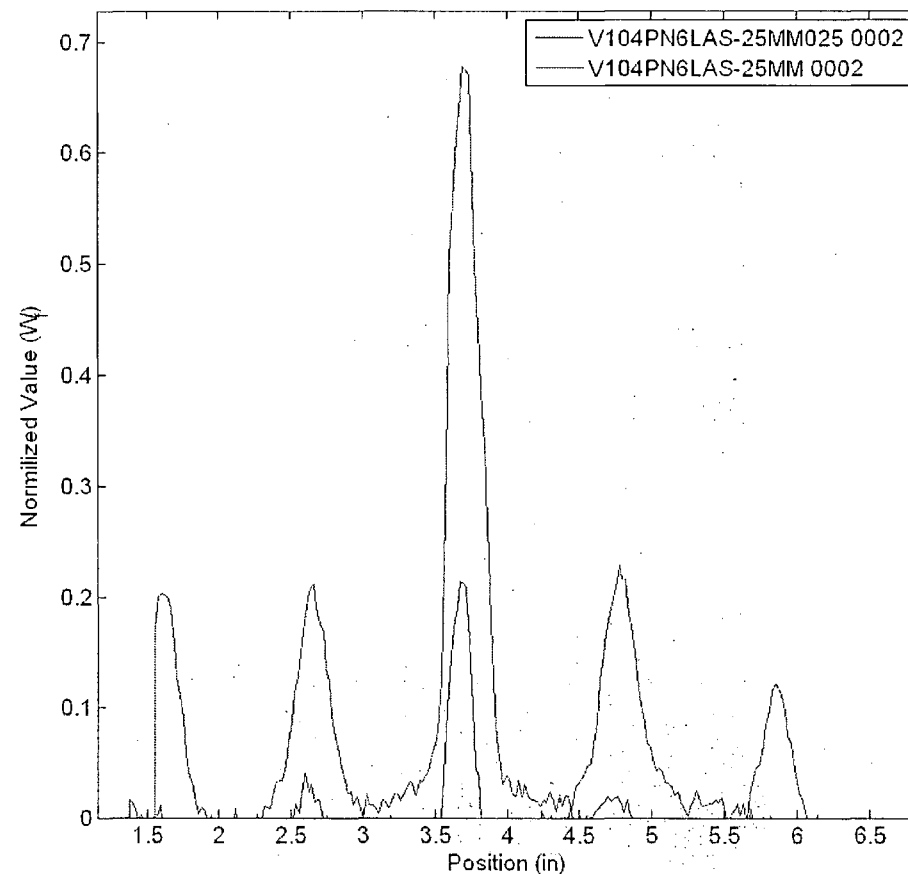


Thermal Data – No T-Seal & 0.025" Gap 5/16"

V104PN6LAS-25MM025 0002.RAW



Panel Number:6L - Gap - 0.025" Max Value:0.68



Panel

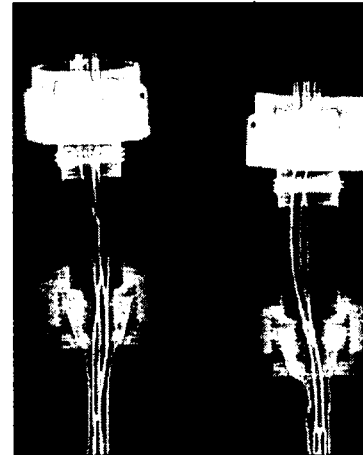
6L - Gap - 0.025"

Center

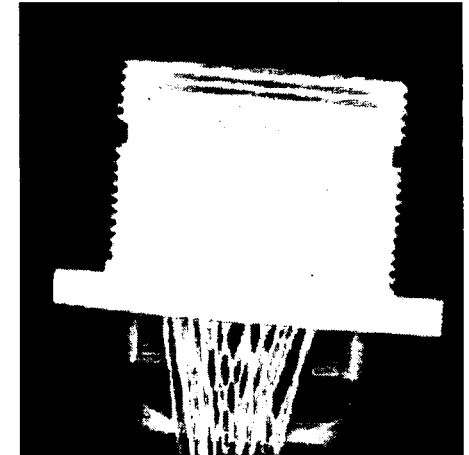
3.9443

Computed Tomography (CT)

- Digital geometry processing is used to generate a three-dimensional image of the inside of an object from a large series of two-dimensional X-ray images taken around a single axis of rotation.
- CT produces a volume of data which can be manipulated, through a process known as "windowing", in order to demonstrate various bodily structures based on their ability to block the X-ray beam.



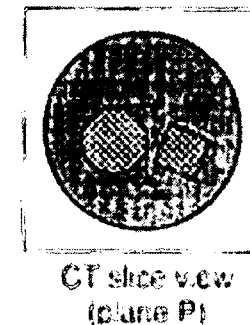
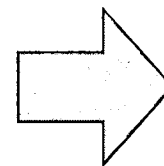
**Small connectors:
Individual pins visible**



**Multi-pin connectors:
Pins superimposed**



**Specimen to be inspected rotates within x-ray beam.
Duration of rotation (currently 4.4 hours) will be
reduced to 8 minutes with faster detector.**



Result:

- Review desired slices within specimen
- Create volumetric reconstructions

CT Validation

Detailed CT Technique Data:

General data:

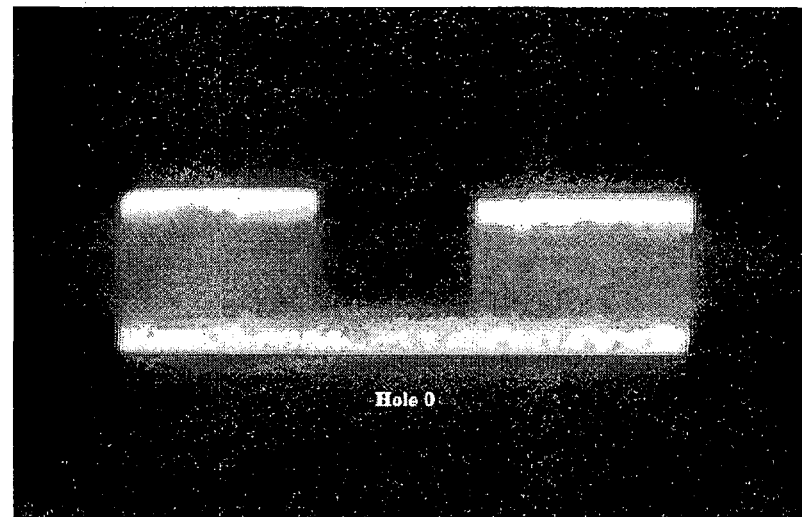
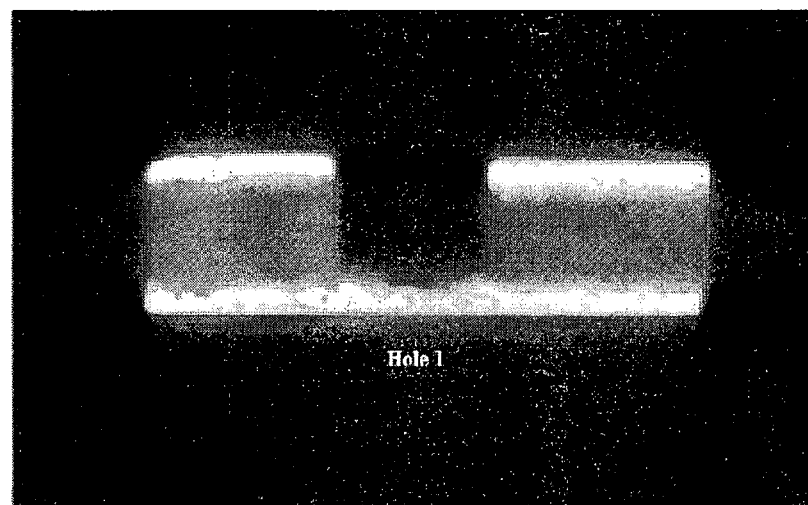
X-ray machine: Philips MG225
(positioned stationary on floor - independent of part manipulator)
Focal spot: small = 0.6 mm
No collimator
Source to center of rotation distance: 55.75 inch
Center of rotation to detector front distance: 7.625 inch
Tube filter: 0.010 inch lead
Detector: Thales FS35 (14 bit, 0.127 mm pixel pitch, fine scintillator)
Detector frame time knob set to 15 (equivalent to approx. 4 sec per frame)
Software: Hytec DAQ 3.1.0, DPS 2.0.6, VIZ: 3.0.3
Hytec part manipulator FCT-P101 (3-axis)
Detector mounted to Hytec part manipulator
Hytec reconstruction cluster with 8 processors

Detector calibration:

Light field: 180 kV, 1.4 mA, 64 frame average (resulting DDR average: ~ 3,300)
Dark field: 64 frame average
Detector not masked
Detector calibration strip fully exposed

Scan acquisition:

180 kV, 3.75 mA
Detector masked with lead except for region of connector to avoid artifacts from aerial saturation
Detector calibration strip also masked with lead
4 frames averaged per turntable position
1,000 turntable positions = 0.36 degrees between positions (software suggested ~700 based on crop region width)
Scan duration: 4 hours 25 minutes per connector



Laser Machining on Standards

- USA NDE has the capability to perform CT on large panels.
- We do have some beam hardening due to a lack of energy in some regions of the panels.
- The resolution of the system is very high on the order of microns.
- We also perform CT on RCC repair samples that come from JSC.



Conclusions

- Comparison metrics can be established to reliably and repeatedly establish the health of the joggle region of the Orbiter Wing Leading Edge reinforced carbon carbon (RCC) panels.
- Using these metrics can greatly reduced the man hours needed to perform wing leading edge scanning for service induced damage. These time savings have allowed for more thorough inspections to be preformed in the necessary areas with out affecting orbiter flow schedule. Using specialized local inspections allows for a larger margin of safety by allowing for more complete characterizations of panel defects.
- The presence of the t-seal during thermographic inspection can have adverse masking affects on ability properly characterize defects that exist in the joggle region of the RCC panels. This masking affect dictates the final specialized inspection should be preformed with the t-seal removed.
- Removal of the t-seal and use of the higher magnification optics has lead to the most effective and repeatable inspection method for characterizing and tracking defects in the wing leading edge.
- Through this study some inadequacies in the main health monitoring system for the orbiter wing leading edge have been identified and corrected. The use of metrics and local specialized inspection have lead to a greatly increased reliability and repeatable inspection of the shuttle wing leading edge.

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